NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

TEP4285

MATERIAL FLOW ANALYSIS

Exercise 5: Dynamic Modelling for the Norwegian Dwelling System

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Author:
Group 5,
Pedro Ferreira,
Varshini Sekaran

Teachers:
Prof. Dr. Daniel Beat MÜLLER,
PhD Cand. Nils DITTRICH,
PhD Cand. Fernando LOPEZ,
M.Sc. Cand. Francis BARRE,
M.Sc. Cand. Emilie ØSTMO,
M.Sc. Cand. Émilien BOURGÉ,

Autumn 2022

NTNU

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Task 1 - Draw a system of mass flows in concrete production and use in the dwelling system, including CO2 emissions from cement production.

Figure 1 shows the use of concrete production and use in dwelling.

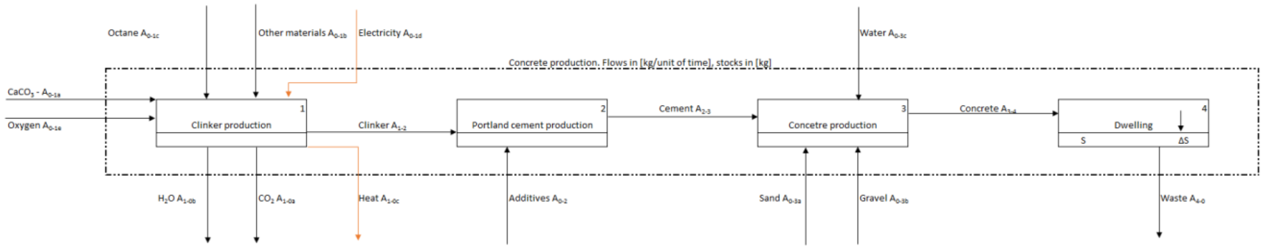

Figure 1 - Flowchart for concrete production and use. Black arrows: mass flows in [kg/unit of time]. Orange arrows: energy flows in [kWh/unit of time].

There are three main processes in concrete production, namely clinker production, cement production, and concrete manufacturing. Quicklime (CaO) is one of the main components of clinker, with a share of 65%. This compound is obtained through the decarbonation of calcium carbonate ($CaCO_3$), following the stochiometric equation:

$$CaCO_3 \rightarrow CaO + CO_2$$

For this system, the decarbonation of limestone happens in process one, demanding energy from octane. The octane combustion follows the equation:

$$2\, C_8H_{18} + \ 25\, O_2 \ \rightarrow \ 16\, CO_2 + \ 18\, H_2O$$

Therefore, oxygen should be included as an input in process 1, while water is an output, along with CO_2. The CO_2 flow ($A_{1\text{-}0a}$) represents both carbon dioxide from the limestone decarbonation and from the octane combustion.

Also, the electricity required in process 1 is represented by the orange arrows. Even though this is not a mass flow, it is included in the diagram to represent the requirements of producing clinker. In an in-depth study, this information could be used to calculate the carbon emissions that are embedded in clinker production by analyzing the carbon intensity of the electricity mix. As no information is given about the release of such energy, it is assumed that electricity is dissipated in the form of heat.

Task 2 - Develop a mathematical model for this system.

a) **Formulate an equation system for the upstream processes of the mass flows in concrete production. Do not include the dwelling stock module (use of concrete) at this point. Instead, the demand for concrete shall be taken as given parameter.**

Table 1 displays the list of equations for the cement production system. Meanwhile, Table 2 shows a list of the parameters that are used for a given concrete demand of 1000 kg/unit of time.

Table 1 - List of equations for the concrete production system in which concrete demand is a given parameter of 1000 kg/unit of time. Mass balance equations are highlighted in blue, while energy flows are highlighted in orange.

Flow name	From	To	Value	Unit/time	Equation
Limestone ($CaCO_3$)	0	1a	113,441	kg	A_{0-1a} = A_{1-2} * s_cao * car_li
Others materials	0	1b	33,939	kg	A_{0-1b} = A_{1-2} + A_{1-0a} + A_{1-0b} - A_{0-1a} - A_{0-1c} - A_{0-1e}
Octane (C_8H_{18})	0	1c	6,588	kg	A_{0-1c} = (A_{1-2} * oc_de) / cv_o
Electricity	0	1d	8775000	kWh	A_{0-1d} = A_{1-2} * el_d
Oxygen (O_2)	0	1e	23,057	kg	A_{0-1e} = A_{0-1c} * or_oc
Carbon dioxide (CO_2)	1	0a	70,17	kg	A_{1-0a} = A_{0-1c} * cop_oc + A_{0-1a} * cop_li
Water (H_2O)	1	0b	9,355	kg	A_{1-0b} = A_{0-1c} * wp_oc
Heat	1	0c	8775000	kWh	A_{1-0c} = A_{0-1d}
Clinker	1	2	97,5	kg	A_{1-2} = A_{2-3} * s_clc
Additives	0	2	32,5	kg	A_{0-2} = A_{2-3} - A_{1-2}
Cement	2	3	130	kg	A_{2-3} = co_d * s_cec
Sand	0	3a	310	kg	A_{0-3a} = co_d * s_sc
Gravel	0	3b	490	kg	A_{0-3b} = co_d * s_gc
Water	0	3c	70	kg	A_{0-3c} = co_d * s_wc
Concrete	3	0	1000	kg	co_d

🟦	Mass-balanced equations
🟧	Energy flows

Table 2 - List of parameters for the concrete production system

Parameter	Symbol	Value	Unit
Share of CaO in clinker	s_cao	0,65	-
Share of other material in clinker	s_mcl	0,35	-
Share of clinker in cement	s_clc	0,75	-
Share of cement in concrete	s_cec	0,13	-
Share of gravel in concrete	s_gc	0,49	-
Share of sand in concrete	s_sc	0,31	-
Share of water in concrete	s_wc	0,07	-
O_2 required per kg of octane	or_oc	3,5	kg
CO_2 produced per kg of octane	cop_oc	3,08	kg
H_2O produced per kg of octane	wp_oc	1,42	kg
$CaCO_3$ required per kg of CaO	car_li	1,79	kg
CO_2 produced per kg of $CaCO_3$	cop_li	0,4397	kg
Calorific value octane	cv_o	44,4	MJ/kg
Energy demand of octane	oc_de	3	MJ/kg
Concrete demand	co_d	1000	kg
Electricity demand	el_d	90000	kWh/kg

Table 2 offers an overview of the parameters used. Three parameters (*or_oc*, *cop_oc*, and *wp_oc*) are derived from the second equation presented in task one. By applying the molar mass of each compound to the equation, we can normalize each mass per 1kg of octane, as described in Appendix 1. A similar approach is used to find *cop_li* but using the equation for the decarbonation of limestone. With the demand for CaO (obtained from the demand of clinker (A_{1-2}) *times* the share of CaO in clinker (*s_cao*)), it is possible to calculate the demand for $CaCO_3$ (*car_li*), using a similar rationale as before, using the molar masses (see Appendix 1).

The result of the quantification is seen in Figure 2.

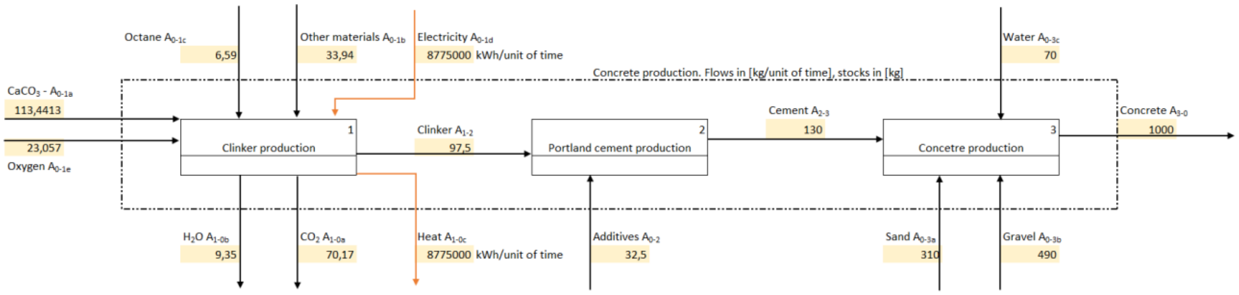

Figure 2 - Concrete production for a concrete demand of 1000 kg/unit of time. Black flows: material layer in [kg/unit of time]. Orange flows: energy layer in [kWh/unit of time].

b) **Find the analytical solution for the CO_2 emissions and perform a sensitivity analysis for this flow. You do not have to show all the calculations but the results. Which parameters have a constant value? Does it make sense to perform a sensitivity analysis for these?**

The analytical solution for the CO_2 equation ($A_{1\text{-}0a}$) is described as:

$$A_{1-0a} = \ co\_d \times s\_cec \times s\_clc\left(\left(\frac{cop\_oc \times oc\_de}{cv\_o}\right) + (s\_cao \times cop\_li \times car\_li)\right)$$

After having the final equation, a sensitivity analysis was performed, as describes in Table 3.

Table 3 - Analytical solution and sensitivity analysis for CO_2 emissions in cement production

f(x)	x	f'(x)	Sensitivity analysis	
			Absolute	Relative
$A_{1\text{-}0a}$ = co_d * s_cec * s_clc [((cop_oc * oc_de)/cv_o) + (s_cao * cop_li *car_li)]	co_d	$(A_{1\text{-}0a})'$ = s_cec * s_clc (((cop_oc * oc_de)/cv_o) + (s_cao * cop_li * car_li))	7,02E-02	1,00E+00
	s_cec	$(A_{1\text{-}0a})'$ = co_d * s_clc (((cop_oc * oc_de)/cv_o) + (s_cao * cop_li * car_li))	5,40E+02	1,00E+00
	s_clc	$(A_{1\text{-}0a})'$ = co_d * s_cec (((cop_oc * oc_de)/cv_o) + (s_cao * cop_li * car_li))	9,36E+01	1,00E+00
	🟩 cop_oc	$(A_{1\text{-}0a})'$ = co_d * s_cec * s_clc (oc_de/cv_o)	2,32E-05	1,02E-06
	oc_de	$(A_{1\text{-}0a})'$ = co_d * s_cec * s_clc (cop_oc/cv_o)	6,76E+00	2,89E-01
	🟩 cv_o	$(A_{1\text{-}0a})'$ = -co_d * s_cec * s_clc ((cop_oc * oc_de)/cv_o^2)	-4,57E-01	-2,89E-01
	s_cao	$(A_{1\text{-}0a})'$ = co_d * s_cec * s_clc (cop_li * car_li)	7,67E+01	7,11E-01
	🟩 cop_li	$(A_{1\text{-}0a})'$ = co_d * s_cec * s_clc (s_cao * car_li)	1,13E+02	7,11E-01
	🟩 car_li	$(A_{1\text{-}0a})'$ = co_d * s_cec * s_clc (s_cao * cop_li)	2,79E+01	7,11E-01

🟩 Constant parameters

In the table above, four parameters are highlighted in green as they are considered to have a constant value. Those are the CO_2 produced per kg of octane (*cop_oc*) and per kg of limestone (*cop_li*). The same is true for $CaCO_3$ required per kg of CaO (*car_li*) and the calorific value of octane (*cv_o*). These four parameters were considered as constants because they are based on physicochemical properties like the molar masses of substances that are empirically proven and will not change. In contrast, parameters as the share of clinker in cement (*s_clc*) are passive of change due to external influence, like the preference of the manufacturer or a change in demand for concrete.

Since these parameters remains constant over time, it does not make sense to perform a sensitivity analysis for them. Note that their sensitivity is not zero. However, one cannot tell how the change in these parameters will affect the referred flow, as their variation is impossible to happen without breaking physicochemical laws. However, Table 3 showed that the most influential parameters are not in the list of constant factors, which is a valid result from this type of assessment.

c) According to your analysis, which parameters have the greatest influence on this flow? What are the limitations of this approach for sensitivity analysis, and how does this compare with an empirical simulation of parameter variation over time (question 4)?

Table 3 shows that the concrete demand, the share of cement in concrete, and the share of clinker in cement has an equally high influence on the CO_2 emissions flow. This is expected since these parameters determine the inter-process flows, and therefore they drive the main economic outputs from each node in the system. It is importance to notice that concrete demand is highly influential in CO_2 emissions, as it determines the cement demand, which determines the clinker demand from process 1, where CO_2 is generated.

Although performing a sensitivity analysis is useful in quasi-stationary systems, it is somehow limited when a dynamic system is considered. That is because the sensitivity analysis only offers a snapshot of the system, and it is uncapable of capturing the parameters variations over time.

For this, a different analysis is necessary using the empirical simulation of parameter variation over time. This has been carried out using MATLAB and SIMULINK in forthcoming questions.

Task 3 - Use the existing Matlab script and Simulink model (for concrete demand to housing) to build an add-on for the concrete/cement production to find the CO_2 emissions. Do this by creating blocks (in Simulink) that represent the different steps of the supply chain. Run the simulation and present a plot of:

a) CO_2 emissions

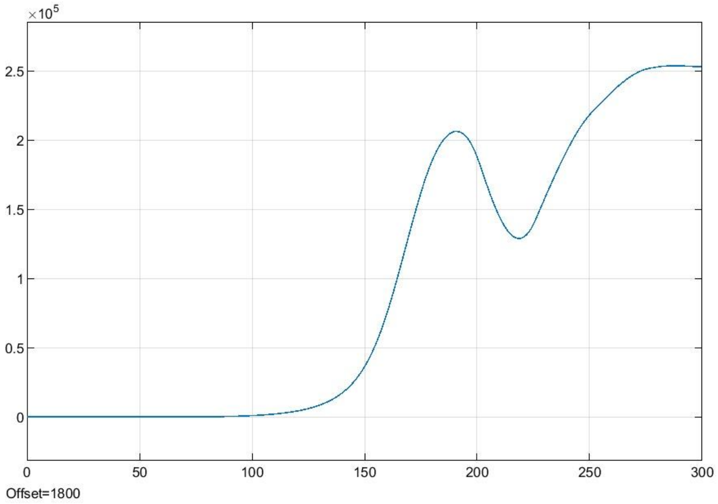

Figure 3 - CO_2 emissions from cement production for dwelling. Plot generated by Simulink in Matlab.

In Figure 3, we observe the CO_2 emission from concrete production has been at a stable low level until 1900s. Exponential growth is seen from the 1940s, with a peak in 1990s. This rapid increase is attributed to the end of World War 2, when cement production accelerated. After the peak, there is a gradual decrease, and the curve hits a low in 2020. This is because there has been an overall decrease in the clinker production in Norway from 2000 to 2020. (Statistics Norway, Norway Environment Agency). From the present-day scenario, CO_2 emission is projected to grow until 2050 and stabilize thereafter.

b) Inflow and outflow (of concrete) to/from use, and stock change

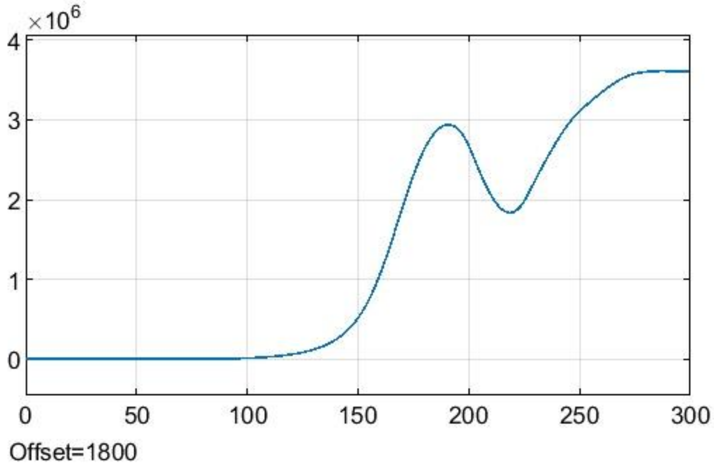

Figure 4 - Concrete demand (inflow to use) for dwelling. Plot generated by Simulink in Matlab.

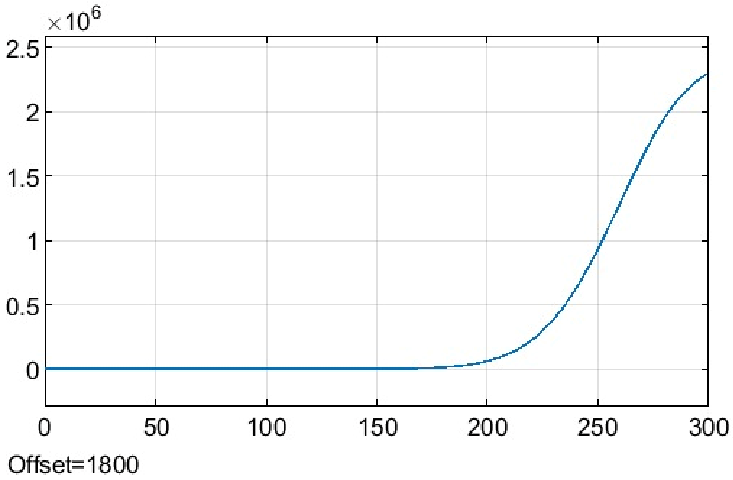

Figure 5 - Concrete waste (outflow from use) in dwelling. Plot generated by Simulink in Matlab.

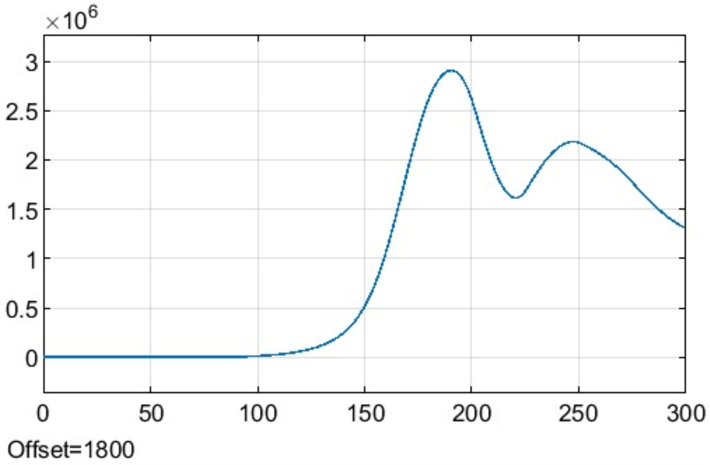

Figure 6 - Concrete stock change in dwelling. Plot generated by Simulink in Matlab.

Figure 4 follows a similar rationale as Figure 3, with the end of WW2 resulting in an exponential increase. There has been a reduction in the demand for dwelling and, hence, concrete from the 1990s until the present, which can be attributed to the rapid increase in building stocks post WW2. However, from now on, since most of old dwellings is reaching the end of its lifetime, an increase in concrete demand is projected, for both refurbishing old building as well as to build new ones. This assumption is supported by Figure 5, where the outflow of concrete from dwellings (here, understood as demolition waste) is steadily increasing from 2020.

c) Stock (of concrete) in use

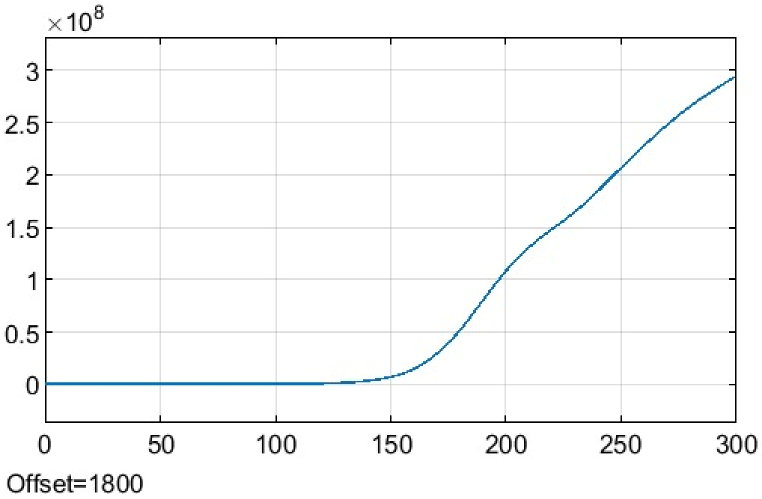

Figure 7 - Concrete stock in dwelling. Plot generated by Simulink in Matlab.

Figure 7 shows that the concrete stock in dwelling is rising continuously from 1950. This can be attributed to the steady growth in population, and more importantly to economic growth and wealth. Economic progress has increased the living standards that is reflected in the demand for floor area of dwellings and construction activity. The most significant growth is observed in the period following the Second World War. Between 1950 and 2000 the demand for dwelling stock by the Norwegian population increased by more than 400%, while the population growth was only 38% (Bergsdal et al 2007). At the same time, demolition activity is almost negligible, and the stock change (Figure 6) therefore follows a very similar path as the construction activity.

d) Drivers (P, PpD, UFApD)

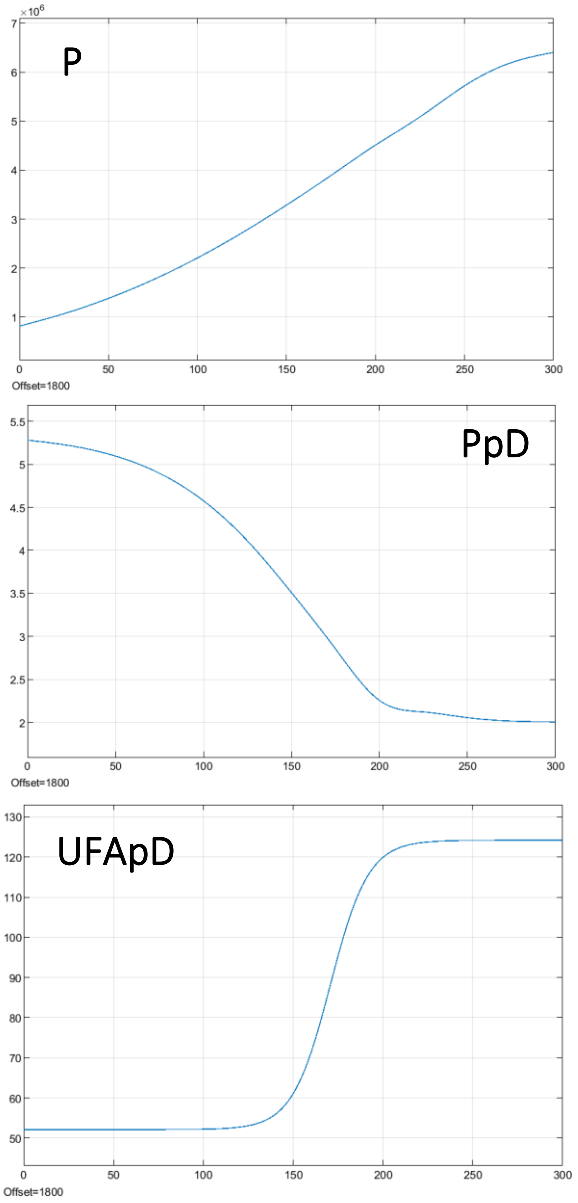

Figure 8 - Drivers for concrete demand in dwelling. P: population, PpD: people per dwelling, UFApD: useful floor area per dwelling. Plot generated by Simulink in Matlab.

Figure 8 shows the plots of three drivers (namely P, PpD and UFApD) from the year 1800 to 2100. Norwegian population (P) has been growing steadily for the last two centuries, from about 880 000 in 1800 and to the present level of about 5.4 million inhabitants. From the plot, it can be inferred that the population will continue to grow but at a slower pace from 2020 onwards (Bergsdal, et al 2007).

PpD is observed to decrease steadily. One of the main forces behind this development has been the advancement of the Norwegian economy, particularly in the last 30 to 40 years, and the subsequent rise in living standards. Moreover, social change has had a great influence on the amount of people living in the same space. Smaller families have become the norm, and different generations no longer cohabit in the same home. Family structures have changed as a result. People who are more educated tend to live alone for longer, and divorce rates have also gone up. All these factors have helped to significantly lower the average number of people per dwelling, which has been observed in Figure 8 (Bergsdal, et al 2007).

While the number of persons per dwelling has decreased, the average size of Norwegian dwellings has increased significantly. The increase in floor area per dwelling was particularly strong after the Second World War, as seen in UFApD in Figure 8. However, we can also observe that this rapid increase slows down after the 2000s. Increased urbanization and smaller urban dwellings support this trend. Also, the price per square meter in urban areas have scaled a lot in the last two decades, which also explains the timid changes since the beginning of the millennium.

Task 4 - Test the long-term sensitivity of CO_2 emissions with respect to different input parameters (P, PpD, UFApD, Tau, M, Clinker factor and Specific Fuel Consumption). Do so by scaling the time series of parameters with a factor that equals 1 for historic years (until present) and that gradually shrinks to e.g. 0.9 for 2100 for parameters with a positive sensitivity (so that population in 2100 is 90% of the base scenario population in 2100). For parameters with a negative sensitivity, use instead a factor going from 1 in historic years to 1.1 in 2100. This way, all simulated changes in the parameters will lead to a decrease in CO_2 emissions, allowing for an easier interpretation of the results. What are the most important parameters in the short and in the long term?

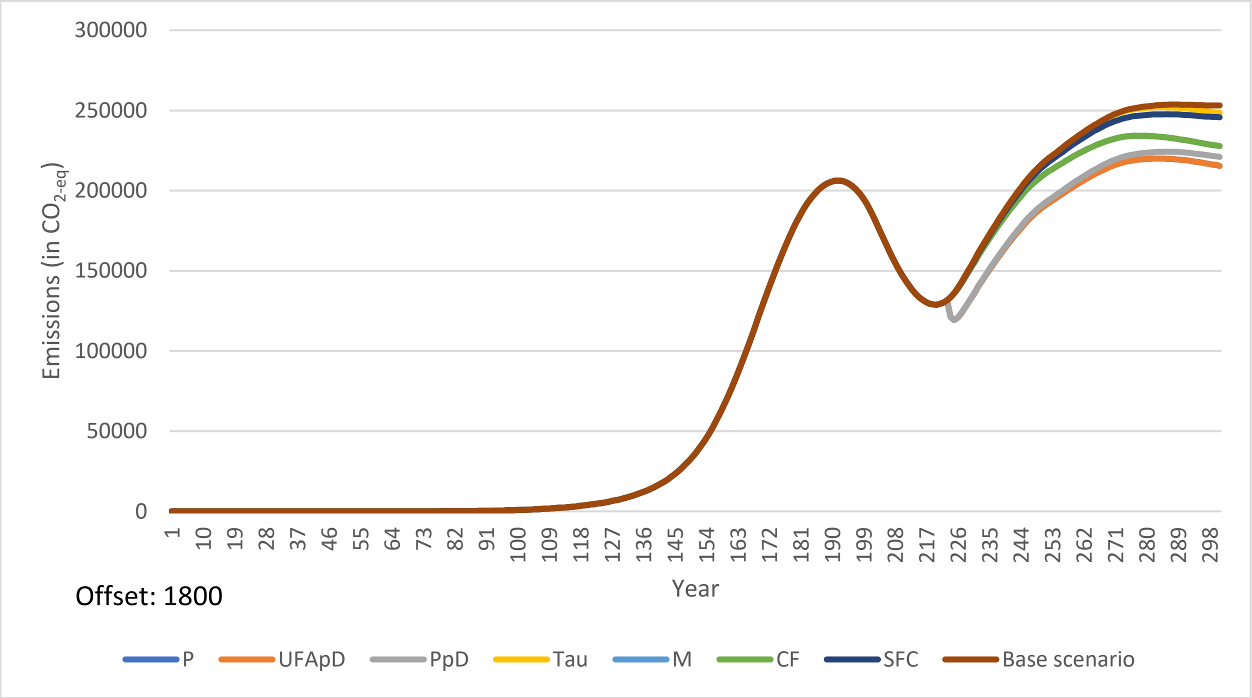

Figure 9 - Lon-term sensitivity of CO_2 emissions per parameter from 1800 to 2100. P: population; UFApD: Useful floor area (UFA) per dwelling; PpD: people per dwelling; Tau: dwelling lifetime; M: concrete density; CF: clinker factor; SFC: specific fuel consumption.

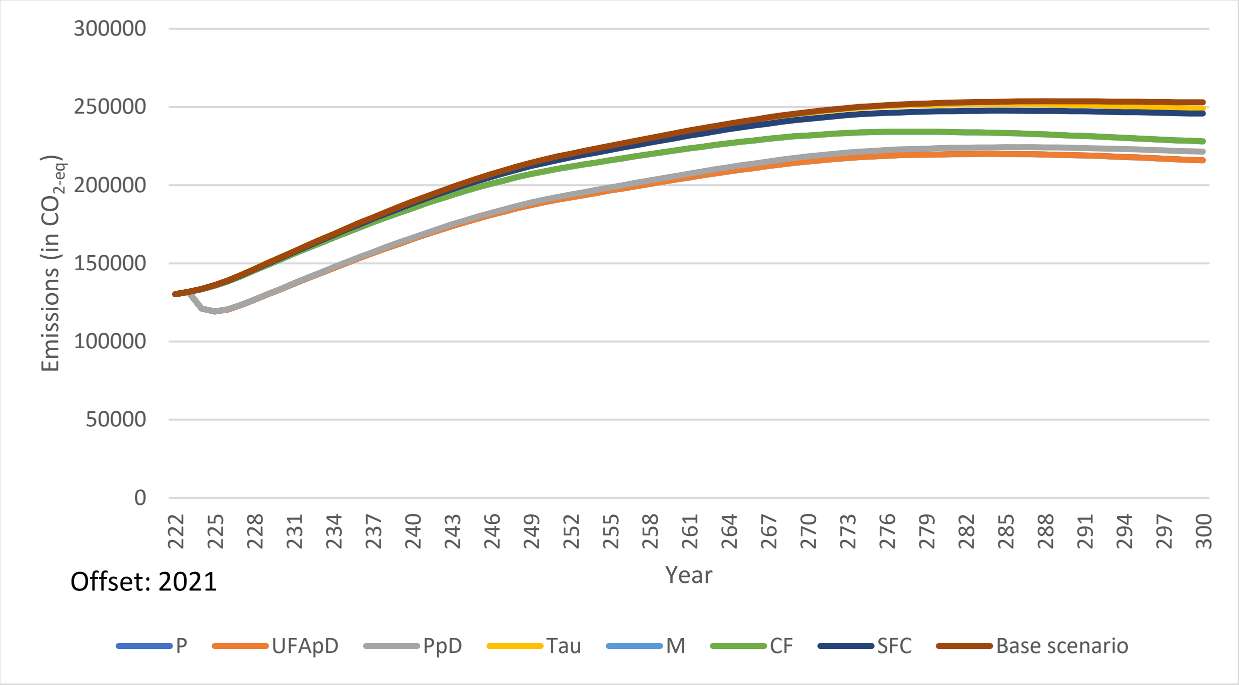

Figure 10 - Close-up on the Lon-term sensitivity of CO_2 emissions per parameter from 2021 to 2100. P: population; UFApD: Useful floor area (UFA) per dwelling; PpD: people per dwelling; Tau: dwelling lifetime; M: concrete density; CF: clinker factor; SFC: specific fuel consumption.

Figure 9 and Figure 10 shows the sensitivity analysis for CO_2 emissions with the time perspective considered. The variation of parameters over time highlights which parameters have more influence in reducing CO_2 emissions in the long-run and which has a clear influence on the short term.

Population, People per Dwelling and Floor area per dwelling are the most important parameters in the short term. This is because reduction in population and increase in people per dwelling reduces the need for construction of new houses which in turn reduces the need for concrete. Similarly, reducing the floor area per dwelling demands less material and thereby reducing CO_2 emissions. In the close-up figure, it is possible to see that the three parameters cause a high decrease in emissions right after 2021. The lower curves are maintained until 2100.

When a longer perspective is considered, the influence of CF and M (blue curve under CF) become clearer, while other parameters like Tau and SFC do not cause a very substantial change in emissions in the long-term. This is important on scenario modelling to determine which parameters should be focused on, to maximize the desired outcome, in this case, reducing emissions.

Task 5 - Develop alternative emission scenarios based on the fictive targets of a 40% and an 85% reduction of CO2 emissions by 2050 compared to 1990 levels. Develop at least 3 scenarios for reaching the 40% target, and at least 1 scenario for reaching the 85% target. Explain the modifications introduced in the base model for the development of each scenario and the reasoning/principles behind measures and scenarios.

Scenario1

In the first scenario, the Norwegian government imposes a regulation that starts in 2022, in which all new dwellings should reduce their useful floor area by 13% when compared to the base scenario trend. We observe that in 2050, the total area reduction is comparable to the UFApD of 1983. According to the policy creator, this will reduce carbon emissions by 40%, while assuring land security for housing in the country.

A) In the first sub-scenario, we assume that the concrete density is going to follow the same trend as in 2022 and reach 0.78 in 2050.

B) In the second sub-scenario, the reduction in floor area reflects in the concrete density M and it gets reduced to 0.71, rather than the projected 0.78 (a 29% reduction) by 2050. By doing this, the demand for concrete reduces which in turn reduces the CO_2 emissions.

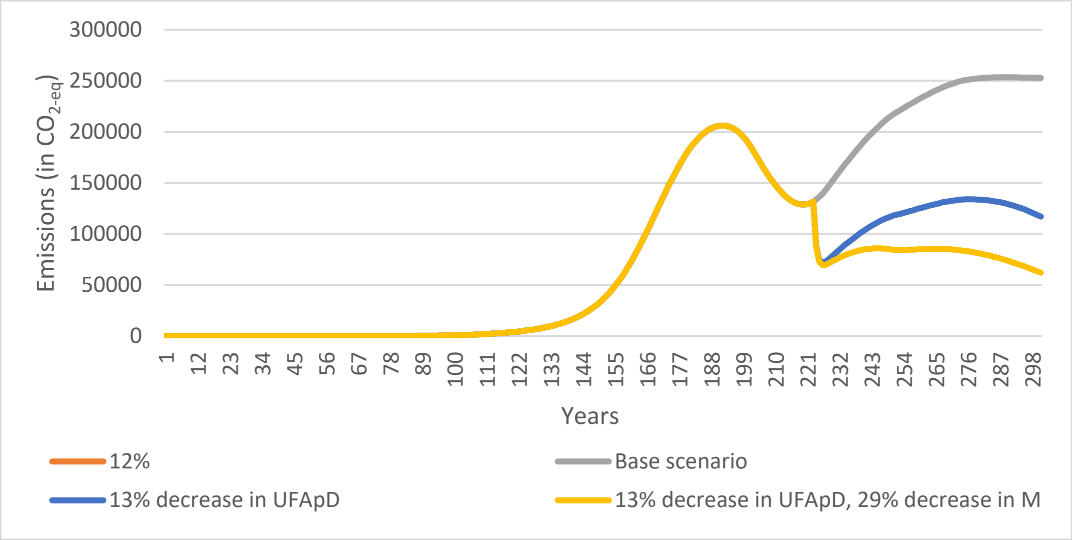

Figure 11 - Results for scenario 1

Figure 11 shows the results for scenario 1. By comparing the two sub-scenarios, reduction in concrete density in addition to reduction floor area has increased the savings in emissions from 46% to 61%.

Scenario 2

In the next scenario, the Norwegian government decides to vote for legislations that prevent the populational growth to decrease the carbon emissions by 40%. With that, the immigrant population keeps decreasing due to the imposition of exorbitant tuition fees for non-EU students. This is aggravated by the approval of unfair policies towards immigrants which causes them to leave the country. This situation results in a huge loss in manpower and the economy shrinks. The financial and socio-economic crisis leads to a 3% populational decrease by 3% in 2050. Also, the crisis forces people to move-in together to improve their financial and mental well-being. This increases the PpD from 2.13 in 2022 to 2.47 in 2050, which is a 20% increase. The result is seen in

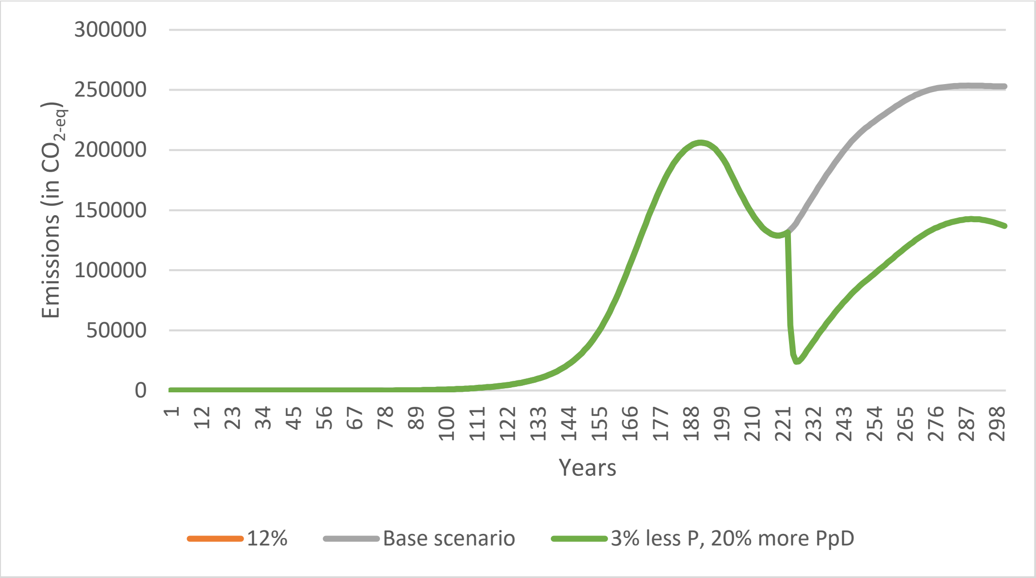

Figure 12 - Results for scenario 2

Figure 12 - Results for scenario 2 shows the result for scenario 2. With the changes in place, a 58% reduction in CO_2 emissions is observer in 2050.

Scenario 3

In the third scenario, the Norwegian construction sector has undergone significant technological changes and the concrete density becomes 0.55 in 2050. This means, 45% of concrete is made from fly ash, aluminum slag and metal slag from other Industries. However, this substitution has reduced the lifetime of buildings by 3 years.

From the above scenarios, we can infer that reduced M has caused significant reduction in CO_2 emissions. So, we were interested in a new scenario where we only change the value of M, and other parameters remain the same. The result we obtained is represented in Figure 13 - Results for scenario 3Figure 13.

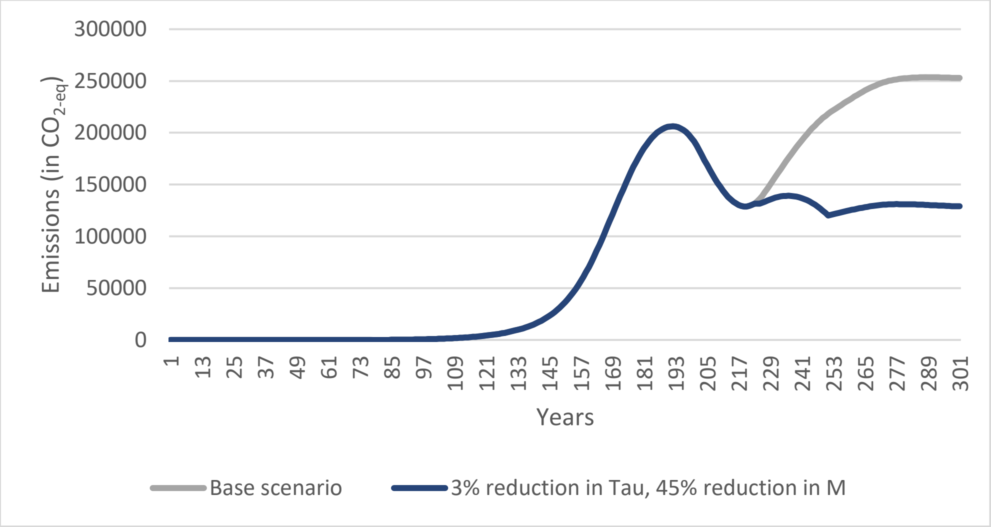

Figure 13 - Results for scenario 3

Scenario 4

In this scenario, Norway has decided to increase the share of substitution to cement to 80%, using renewable materials like wood. Thus, the M value becomes 0.155 in 2050. Even the production of the remaining 20% concrete has been made very efficient. That is, the share of clinker in the cement is reduced from 75% to 70%, which is the minimum amount required by the European standards. In addition, we assume that the fuel used is a mixture of octane and a carbon neutral fuel like biofuel or hydrogen. This in turn reduces the share of fuel energy required from octane from 3MJ/kg to 1.25MJ/kg. This scenario has a 85% reduction in CO_2 emissions by 2050. The result is displayed in Figure 14.

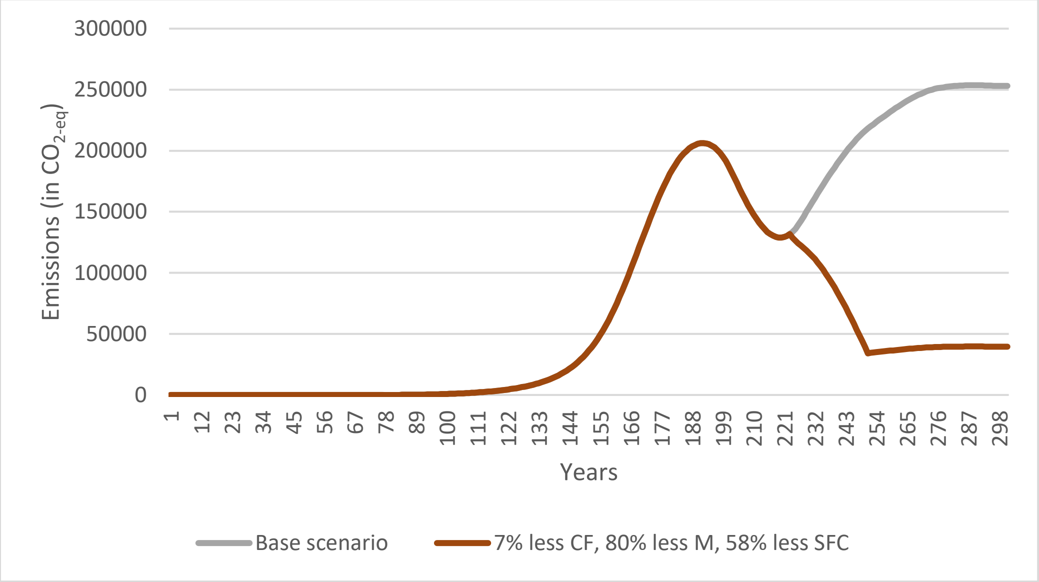

Figure 14 - Result of scenario 4

Task 6

a. What are the technological options for reaching the targets? Is there a need to look for measures beyond technological improvement? Which factors can be influenced by the cement industry, which factors are beyond the cement industry's influence?

Technological options/Substitution options:

-Burnt clay

The manufacture of cement involves subjecting limestone to heat treatments at temperatures higher than 1450°C. This causes the rock to release CO_2, which alone makes up about 60% of the total emissions. Eco-cement or burnt clay is more eco-friendly because it does not give off CO_2 during heat treatment, other than those emissions resulting from the heating process. However, the volumes are much lower because the clay does not need to be heated to more than between 600°C and 800°C (SINTEF, 2022).

-Wooden construction materials

Forests are natural carbon sinks that absorb CO_2 over its lifetime until it is released again when combusted or by decay. Hence, if the CO_2 sequestered by timber is harvested before their release, it also decreases the atmospheric concentration. In this way, we can transfer stored carbon from forests into cities. By doing this we also limit the risk of natural depletion of forests (caused by increasing temperatures and other natural disturbances). Replacing concrete with materials made from wood can, therefore, reduce the amount cement manufactured, which in turn would mitigate GHG emissions.

-Bio-cement

Bio-cement is a replacement material that has the potential to reduce the CO_2 emissions from the production of cement. Bio-cement stimulates native soil bacteria to cement soil particles together through a process known as Microbial Induced Calcite Precipitation (MICP). This process - referred to as bio-cementation - results in a product that may serve as an appropriate substitute for cement in construction projects (Vågerö, O., 2020). Bio-cement in the form of dry powder is mixed with water. This resulting solution is then fed to native soil bacteria, which grow in proportion to the amount of nutrients, cementing the soil together. Cemented soil particles form a hardened, less permeable material like limestone.

-Ashcrete

Fly ash, a byproduct of coal combustion which can be used to make green concrete. Ashcrete is a recycled fly ash-based alternative to conventional concrete. Fly ash is mixed with lime and water to make it strong and durable, like conventional cement. Other advantages of fly ash over conventional concrete include less bleeding, greater concrete strength, and less shrinkage.

In addition to the substitution technologies, the factors which are beyond the control of cement industries include the people’s behavior and choices. Choice to live in a smaller dwelling, choice of living in joint families/co-living, and the choice to have less number/no kids (reduction in population) are significant drivers of cement industries which cannot be overlooked.

Factors that can be influenced or improved by cement industries

-CCS

Carbon Capture and Storage is a very promising approach that can be employed in the cement industries to prevent the release of CO_2 generated during the clinker production, by injecting the CO_2 in suitable underground storage reservoirs. Capture processes can be grouped in three categories depending on the industry type: post combustion, pre combustion, oxyfuel combustion.

For cement production, oxyfuel combustion is of importance for the reduction of CO_2. In this case, the primary fuel is combusted in oxygen instead of air, which produces a flue gas containing mainly water vapor and a high concentration of CO_2 (80%). The flue gas is then cooled to condense the water vapor, which leaves an almost pure stream of CO_2.

b. Compare the cumulative emissions (sum of emissions from 2015 to 2050) of the 40% target scenarios. Is the setting of emission targets for 2050 compared to 1990 a useful way for reducing cumulative emissions?

c. In order to limit the average global temperature increase to 2 degrees Celsius, the IPCC recommends a global emissions reduction by 2050 of 50-85% compared to 1990 levels. Which factors need to be considered when translating this global target into targets of the Norwegian cement industry (this is, an individual sector within an industrialized country)? Reflect about the different development levels among countries.

Most of the CO_2 emissions in concrete production occur during the calcination process. Therefore, this is the stage that needs to be targeted by the Norwegian cement industry. One solution is to find alternatives for clinker like fly ash, silica fumes, calcinated clays, burnt furnace slag, steel slag, or aluminum slag. These alternatives are mostly bi-products or waste from other industries which can be valorized. Carbon capture and storage at the end of clinker production can be employed to reduce emissions into the atmosphere. Yet another way to reduce the CO_2 emissions is to replace fossil fuel for heating (during clinker production) with greener alternatives. This can include renewable energy sources, biofuel, or by incinerating municipal waste.

The demand for concrete varies according to the development levels of the countries. For instance, for a developed country like Norway, the demand will be much less than in a developing country like India or China. This is because most of the construction happened post-industrial revolution and WW2 and hence a significant share of the demand will go to refurbishment and maintenance. However, it should also be considered that Urbanization still takes place, which causes the cities to expand and hence this increases the demand for concrete. But these levels are lower than in developing countries.

Industrialized countries like Norway are in an advantageous position to implement costly technologies like CCS compared to developing countries. The latter should focus on using alternatives to clinker by using materials like fly ash, slag, among others, as discussed in the previous question to reduce their CO_2 emissions. Carbon markets are another promising way to achieve equitable climate justice. This benefits both the developing and developed countries.

d. New research (see Xi et al., 2016) suggests that cement stocks can act as carbon sinks during their use phase, thanks to the natural carbonation process. How could this affect your results?

Once it is in place, concrete naturally absorbs CO_2 from the atmosphere over its lifetime. However, it is not enough to fully counter the emissions released during its production. New research has improved the absorption capacity of cement so that it can act as carbon sink in its use phase as described by Xi et al., 2016.

If this type of concrete is applied, our results will significantly improve, as the CO_2 emission during clinker production and transportation will be balanced out by the capacity of concrete stocks to act as carbon sinks during the use phase. It is possible for the cement stock to allow for net-negative emissions if the absorption of carbon over the lifetime of the cement stock is greater than the emissions during production and transport. This is possible if the absorption capability and absorption rate of CO_2 by cement can be further improved.

Task 7 - Discuss the usefulness and relevance of stock-driven models compared to consumption-driven models.

Consumption driven models assume that customers are key to prosperity of all. It believes that supply follows the demand/consumption and manufacturers aim to satisfy customer’s demands. From an economic point of view, we can see that either flow of production or flow of consumption drives the model. However, from a sustainability perspective, it is more relevant to use stock driven model rather than consumption driven model. Because only if the products become old, do we drop them and buy new products. For instance, if we have immigrants and we need to provide them housing, we need to see the existing construction (stock in use) and not the inflow. The flows can then be used as a means of adjustment to the building and construction stocks.

While most products with long lifetime like cars, buildings, furniture come under the stock driven model, it would be appropriate to consider products with short life span as flow driven. Examples include food, newspapers etc. Because for all these, we need a constant supply. There is also a special case of products like fashion. The industry uses marketing and advertising to make the consumer feel inadequate and makes them buy new clothes. This makes it a flow driven system.

Therefore, segregating between stock or consumption driven is not black and white and varies depending on the application. The paradigm of neo classical economics focusing on production and manufacturing is not wrong, but it is not very useful when addressing questions related to satisfying human needs with a limited environment.

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Appendix 1

The parameters *or_oc*, *cop_oc*, and *wp_oc* were calculated as follows:

1) The stochiometric equation for octane combustion was represented in terms of mass (in kg), by using the molar mass (mm).

$$2\ C_8H_{18} +\ 25\ O_2\ \rightarrow\ 16\ CO_2 +\ 18\ H_2O$$

$$\frac{2\ (mm_{octane}) + 25\ \left(mm_{O_2}\right) \rightarrow 16\ \left(mm_{CO_2}\right) +\ 18\ (mm_{H_2O})}{1000}$$

2) The molar mass of each substance was inserted in the equation, as follows:

$$\frac{2\ (114.23\ g/mol) + 25\ (32\ g/mol) \rightarrow 16\ (44.01\ g/mol) +\ 18\ (18.02\ g/mol)}{1000}$$

$$0.228\ kg_{octane} +\ 0.8\ kg_{O_2}\ \rightarrow\ 0.704\ kg_{CO_2} + 0.324\ kg_{H_2O}$$

3) The equation is normalized by 1kg of octane, we have:

$$1\ kg_{octane} +\ 3.5\ kg_{O_2}\ \rightarrow\ 3.08\ kg_{CO_2} + 1.42\ kg_{H_2O}$$

$$1\ kg_{octane} +\ or\_oc \rightarrow\ cop\_oc + wp\_oc$$

The same is valid for the decarbonation od $CaCO_3$ and the parameters *car_li* and *cop_li.*

$$CaCO_3 \rightarrow CaO + CO_2$$

$$0.100\ kg\ _{CaCO_3} \rightarrow 0.0561\ kg_{CaO} +\ 0.044\ kg\ _{CO_2}$$

Normalizing per 1 kg of CaO:

$$1.78\ kg\ _{CaCO_3} \rightarrow 1\ kg_{CaO} +\ 0.784\ kg\ _{CO_2}$$

$$car\_li \rightarrow 1\ kg_{CaO} +\ 0.784\ kg\ _{CO_2}$$

Normalizing per 1 kg of $CaCO_3$:

$$1\ kg\ _{CaCO_3} \rightarrow 0.561\ kg_{CaO} +\ 0.44\ kg\ _{CO_2}$$

$$1\ kg\ _{CaCO_3} \rightarrow 0.561\ kg_{CaO} +\ cop\_li$$